Realistic Magnetohydrodynamical Simulation of Solar Local Supergranulation

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Abstract.

Three-dimensional numerical simulations of solar surface magnetoconvection using realistic model physics are conducted. The thermal structure of convective motions into the upper radiative layers of the photosphere, the main scales of convective cells and the penetration depths of convection are investigated. We take part of the solar photosphere with size of 60×60 Mm in horizontal direction and by depth 20 Mm from level of the visible solar surface. We use a realistic initial model of the Sun and apply equation of state and opacities of stellar matter. The equations of fully compressible radiation magnetohydrodynamics with dynamical viscosity and gravity are solved. We apply: 1) conservative TVD difference scheme for the magnetohydrodynamics, 2) the diffusion approximation for the radiative transfer, 3) dynamical viscosity from subgrid scale modeling. In simulation we take uniform two-dimesional grid in gorizontal plane and nonuniform grid in vertical direction with number of cells $600 \times 600 \times 204$. We use 512 processors with distributed memory multiprocessors on supercomputer MVS-100k in the Joint Computational Centre of the Russian Academy of Sciences.

1. Introduction

The convection near solar surface develops on the different space and time scales. Numerical simulation provides useful information about evolution of convective structures and helps to construct consistent models of the physical processes underlying of observed solar phenomena. We conduct an investigation of the temporal evolution and growth of convective modes on scales supergranulation in a three-dimensional computational box with imposed initially uniform weak magnetic field. In previous work by the author [Ustyugov (2006)] it was shown that collective motions of small convective cells of granulation expels weak magnetic field on the edges cells at mesogranular scales. Average size of such cells is 15-20 Mm and the lifetime is 8-10 solar hours. In article [Rast (2006)] it was suggested that development of large spatial and long temporal mesogranular and supergranular scales naturally arise as result the collective advective interaction of many small-scale and short-lived granular plumes. Simulation of solar photosphere convection [Stein (2006)] in a computational domain of size 48 Mm in horizontal plane and 20 Mm in depth showed that the sizes of convective cells increase with depth. The purpose of this work is to investigate the effect magnetic field on the development of convection on scale supergranulation in a region of size 60 Mm in the horizontal plane and 20 Mm in depth.

2. Numerical method

As initial state we take the distribution of the main thermodynamic variables with radius from the Standard Solar Model [Christensen-Dalsgaard (2003)] with parameters $(X, Z, \alpha) = (0.7385, 0.0181, 2.02)$, where X and Y are hydrogen and helium abundances by mass, and α is the ratio of mixing length to pressure scale height in the convection region. We used the OPAL opacity tables and the equation of state for solar matter [Iglesias (1996)].

The compressible nonideal magnetohydrodynamics equations are solved:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} = 0 \tag{1}$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot \left[\rho \vec{v} \vec{v} + \left(P + \frac{B^2}{8\pi} \right) I - \frac{\vec{B} \cdot \vec{B}}{4\pi} \right] = \rho \vec{g} + \nabla \cdot \hat{\tau} \tag{2}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\vec{v} \left(E + P + \frac{B^2}{8\pi} \right) - \frac{\vec{B} \left(\vec{v} \cdot \vec{B} \right)}{4\pi} \right] = \frac{1}{4\pi} \nabla \cdot \left(\vec{B} \times \eta \nabla \times \vec{B} \right) + \nabla \cdot (\vec{v} \cdot \hat{\tau}) + \rho \left(\vec{g} \cdot \vec{v} \right) + Q_{rad} \tag{3}$$

$$\frac{\partial \vec{B}}{\partial t} + \nabla \cdot \left(\vec{v} \vec{B} - \vec{B} \vec{v} \right) = -\nabla \times \left(\eta \nabla \times \vec{B} \right) \tag{4}$$

here ρ is the density, P is the pressure, $\vec{v}$ is vector of the velocity, $\vec{B}$ is vector of the magnetic field, $\vec{g}$ is vector of the gravitation, $E = e + \rho v^2/2 + B^2/8\pi$ is the total energy, Q_{rad} is the energy transferred by radiation and τ is the viscous stress tensor. The influence of small scales on large scale flows was evaluated in terms of viscous stress tensor and the rate of dissipation was defined from buoyancy and shear production terms [Canuto et al. (1994)]. The evolution of all variables in time was found using an explicit TVD[Total Variation Diminishing] conservative difference scheme ([Yee et al. (1990)])

$$U^{n+1}_{i,j,k} = U^n_{i,j,k} - \Delta t L(U^n_{i,j,k}), \tag{5}$$

where $\Delta t = t^{n+1} - t^n$ and the operator L is

$$L(U_{i,j,k}) = \frac{\tilde{F}_{i+1/2,j,k} - \tilde{F}_{i-1/2,j,k}}{\Delta x_i} + \frac{\tilde{G}_{i,j+1/2,k} - \tilde{G}_{i,j-1/2,k}}{\Delta y_j} + \frac{\tilde{H}_{i,j,k+1/2} - \tilde{H}_{i,j,k-1/2}}{\Delta z_k} + S_{i,j,k} \; . \tag{6}$$

The flux along each direction was defined by the local-characteristic method as

$$\tilde{F}_{i+1/2,j,k} = \frac{1}{2} \left[F_{i,j,k} + F_{i+1,j,k} + R_{i+1/2} W_{i+1/2} \right] \; . \tag{7}$$

$R_{i+1/2}$ is the matrix whose columns are right eigenvectors of $\partial F/\partial U$ evaluated as a generalized Roe average of $U_{i,j,k}$ and $U_{i+1,j,k}$ for real gases. $W_{i+1/2}$ is the matrix of numerical dissipation. The term $S_{i,j,k}$ represents the effect of gravitational forces and radiation. Time step integration is by third-order Runge-Kutta method [Shu & Osher (1988)]. This scheme is second-order in space and time. Central differences were used for the viscous term, and the diffusion approximation was applied for the radiative term in the energy equation. We used a uniform grid in the x and y directions and a nonuniform grid in the vertical (z) direction. Periodic boundary conditions were used in the horizontal directions and the top and bottom boundary conditions were choosen to be

$$v_{z,k} = -v_{z,k-1}, v_{x,k} = v_{x,k-1}, v_{y,k} = v_{y,k-1}$$
$$dp/dz = \rho g_z, p = p(\rho), e = const$$
$$B_x = B_y = 0, dB_z/dz = 0$$

that is, reflection for the z component of velocity, outflow for the x and y components. The pressure and density were derived from the solution of the hydrostatic equation, using the equation of state by constant value of the internal energy.

3. Results

We imposed initially the homogeneuos vertical magnetic field with strength of 50 G. For the magnetic diffusivity we take constant value $\eta = 1.1 \times 10^{11}\text{cm}^2\text{sec}^{-1}$. We carried out calculations in the region of $60 \times 60 \times 20$ Mm on the grid with $600 \times 600 \times 204$ cells during of 24 solar hours. On the figures 1-3 the results of the MHD numerical simulation of development of the convection in the horizontal plane near solar surface are presented. We find that the magnetic field concentrates in extended regions similar sunspot with diameter about 5 Mm and in thin sheets on the boundary of supergranular cells. In these regions we reveal the increase of strength of the magnetic field to values 700-800 G, the decrease of temperature on few thousand kelvin, the small values of the vertical component of velocity in average about 0.05 km/sec and as result full absence of the convective motion. The magnetic pressure prevents the inflow of the material from outside of sunspot and thus the transfer of radiation energy is suppressed. Inside of supergranular cell the value of vertical component of the magnetic field is very small about 1 G and less. Diverging convective flows from the center supergranular expels weak magnetic field to the edges of convective cell. An average size of the supergranular cells is 20-30 Mm. A material moves from the center of supergranular with the velocity of about 1-1.5 km/sec. The maximum value of the magnetic field in the computational domain is 2000 G.

Inside of supergranular we have a typical picture of evolution of convection on the scale of granulation with average sizes of the cells about 1.5 Mm and with lifetime about 4-5 minutes [Stein & Nordlund (1998)]. Here we see wider upflows of warm, low density, and entropy neutral matter and downflows of cold, converging into filamentary structures, dense material. We observe a continuous picture of formation and destruction of granules. The granules with highest pressure grow and push matter against neighboring granules, that then shrink

and disappear. Ascending flow increases the pressure in the center of granule and upflowing fluids decelerates motion. This process reduces heat transport to surface and allows the material above the granule to cool, become denser, and by action of gravity to move down. We observe a formation of new cold intergranule lane splitting the original granule.

From figure 4 we can see properties of turbulent convection on depth 0-4 Mm. In this region the cold blobs of the matter moves down by maximum of velocity of about 4 km/sec and the Mach number M=0.6. The downdrafts has different and very complicate vertical structure. One part of the downdrafts travels on small distance from the surface and becomes weak enough to be broken up by the surrounding fluid motion. Another part of the downdrafts conserves a motion with high velocity and moves on the distance about 6 Mm. We observe that different nature of such behavior is provided by the initial conditions of downdrafts formation. There are places on solar surface where the material moves from different sides to one point and here we find powerful vorticity motions of matter. Due to action of strong compressibility effects we observe quick output of internal energy and formation of downdrafts with maximum of values of the vertical velocity. We detect extended regions with size about 5 Mm in a diameter where turbulent convection is fully disappeared.

On the depthes from 5 Mm to 8 Mm we reveal more quiet character of the convective flow than in the turbulent zone. Below 8 Mm we see clearly the separate large scale density fluctuations and the streaming flow of the material which similar to jets with the largest value of the average velocity equal to 1 km/sec. In these places the magnetic field has value about 300 G. Besides we find on depthes bigger than 10 Mm the separate regions of localization of the huge magnetic energy with values of magnetic field in range from 800 to 1000 G (Fig.5). Distances between these places with strong concentration of the magnetic field is comparable with scales development of the local solar supergranulation. The convective motion in different parts of photosphere leads to continuous changes of topology of the magnetic field. We find inside of the supergranular cell many magnetic loops with big negative values of the vertical component of the magnetic field.

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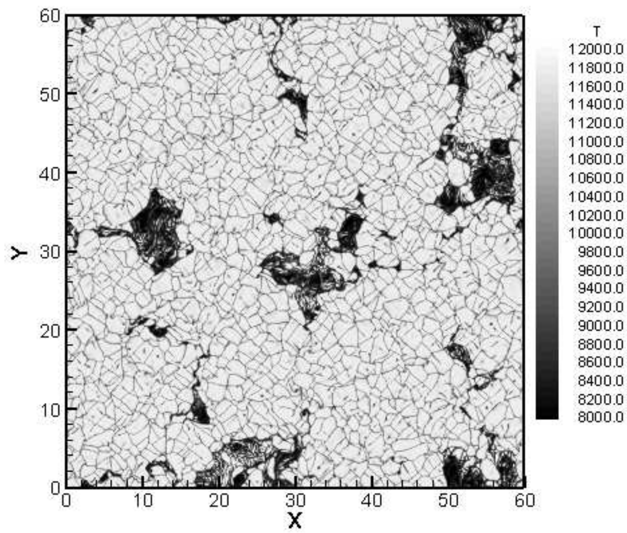

Figure 1. The contours of temperature on a horizontal plane near solar surface. The units of temperature is Kelvin.

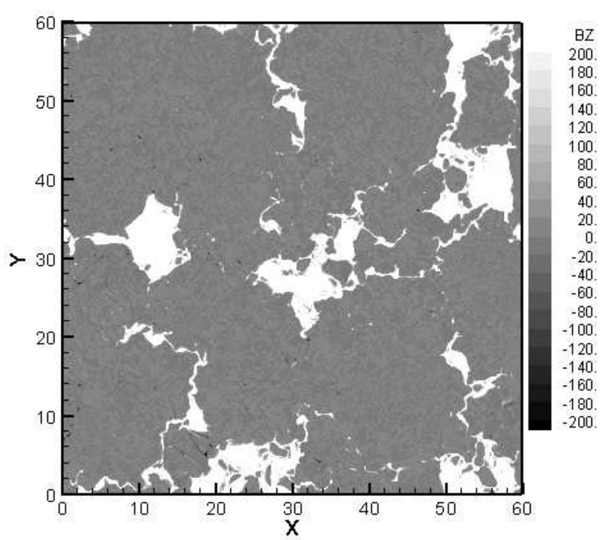

Figure 2. The contours of vertical component of magnetic field on a horizontal plane near solar surface. The units of magnetic field is Gauss.

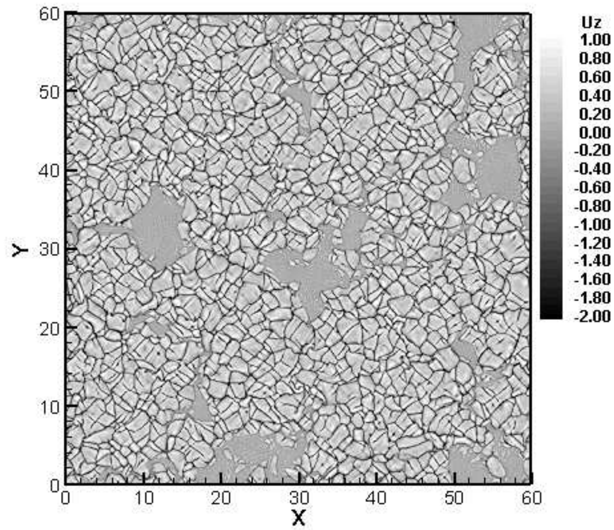

Figure 3. The contours of vertical component of velocity on a horizontal plane near solar surface. The units of velocity is km/sec.

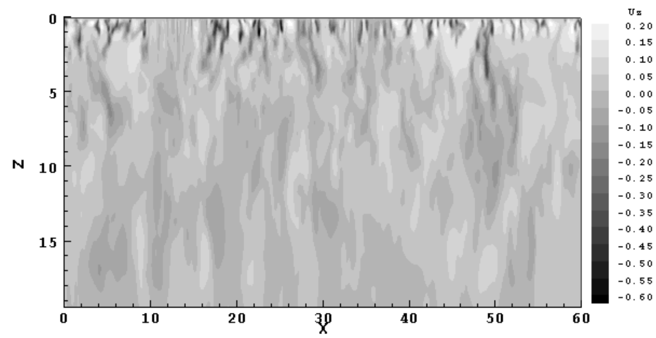

Figure 4. The contours of vertical component of velocity in a vertical plane. The units of velocity in value of speed of sound.

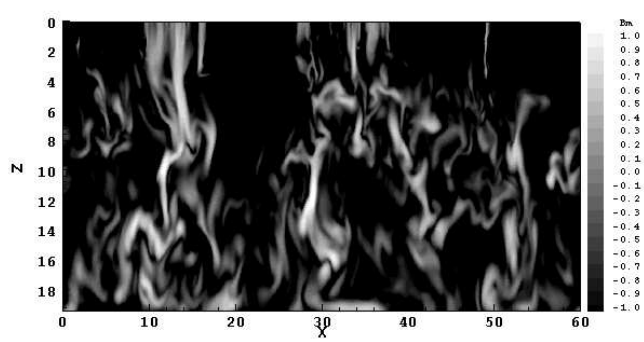

Figure 5. The contours of magnetic energy (in nondimensional units) in a vertical plane.